Towed Array Hydrodynamic Research in the Naval Research Enterprise Intern Program (NREIP)

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NEWPORT

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ABSTRACT

This memo reproduces a presentation describing the towed array hydrodynamic tests performed by the Naval Undersea Warfare Center (NUWC) Division, Newport, RI, under the Naval Research Enterprise Intern Program. The tests, conducted in June 2007 at the Naval Surface Warfare Center's David Taylor Model Basin in Carderock, MD, were designed to measure the turbulent boundary layer velocity profiles, mean wall shear stress, and wall pressure fluctuations on an experimental towed array. The research objectives, experimental approach, measurement techniques, and preliminary results are provided.

ADMINISTRATIVE INFORMATION

This memo was prepared under the Naval Research Enterprise Intern Program and the In-House Laboratory Independent Research (ILIR) Program. The sponsoring activity is the Office of Naval Research, program manager Kirk Jenne (ONR 03R).

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1. INTRODUCTION

In June 2007, the Naval Undersea Warfare Center (NUWC) Division, Newport, RI, performed towed array hydrodynamic tests under the In-House Laboratory Independent Research Program. Test participants included research interns from Cornell University and the Georgia Institute of Technology, mentored by personnel from NUWC Division Newport.

The tests, conducted at the Naval Surface Warfare Center's David Taylor Model Basin in Carderock, MD, were designed to measure the turbulent boundary layer velocity profiles, mean wall shear stress, and wall pressure fluctuations on an experimental towed array.

This memo describes the tests conducted and provides preliminary test results.

2. TEST OBJECTIVES, DESCRIPTION, APPROACH, AND RESULTS

The objectives, experimental approach, measurement techniques employed in the towed array hydrodynamic testing, along with preliminary findings, are contained in the presentation that follows.

3. SUMMARY PRESENTATION

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Towed Array Hydrodynamic Research in the ONR NREIP Summer Internship Program

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June – August 2007

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Navy Problems Addressed

- Towed arrays are the primary acoustic sensor for submarines but have limited operational use and reliability resulting in high maintenance costs.
- Lack of hard data exists on mechanical and hydrodynamic forces.
- Causes of failure are related to the handling system and flow induced stresses on the array during towing.
- Several working groups have performed comprehensive reviews of all towed arrays and handlers, across all platforms, and developed a list of top issues and recommendations:
  - The study found that most simple problems had been corrected by the work of previous review teams but the more complex issues of hydrodynamic forces on the array had not been addressed.
  - The report noted that there is no consistency in ship guidelines dictating which maneuvers would minimize array failure.

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Research Objectives

The results of this project will provide:

- Better definitions of towed array stresses and forces due to turbulent boundary layer forcing, to allow improved array designs.
- Modification of array testing to more accurately stress arrays before delivery to the fleet.
- Improvement of array specifications to ensure delivered products are compatible with actual environmental conditions.
- Improved flow noise models.
- Improved knowledge of the turbulent boundary layer flow field applicable to very long cylinders at high Reynolds numbers.

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Experimental Approach

- An array of wall pressure sensors is used to measure the wavenumber frequency spectra. Scaling these spectra requires measurements of the turbulent boundary layer characteristics.
- A stereo particle image velocimetry (SPIV) system custom made for use in the tow tank, allows measurements of the mean and fluctuating 3 dimensional velocity field along the length of the array.
- A load cell at the array tow point is used to measure the total drag on the array. The spatially averaged mean wall shear stress on the array is determined from this measurement. This is a boundary layer parameter used for scaling spectra and the velocity measurements.
- These three measurements provide sufficient information to analyze the turbulent boundary layers on the array, and identify the sources of flow noise and flow induced noise which contribute to array self noise and also array internal stresses.

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Tow Tank Testing Personnel at CDNSWC David Taylor Model Basin

Test Team

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David Taylor Model Basin Experimental Facility

- Towing tests were conducted using Carriage 5 at the Naval Sea Systems Command (NAVSEA) Carderock high-speed towing basin, also known as the David Taylor Model Basin.

Carriage 5

View of Towing Basin at Location of SPIV Measurements

(See http://www.dt.navy.mil/hyd/fac/tow-bas/hig-spe-bas/index.html)

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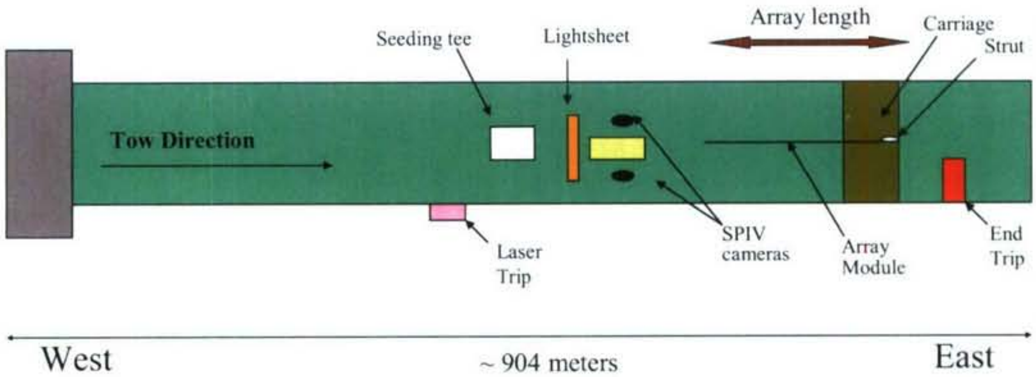
Test Details: Plan View of Components in the Tow Tank



Schematic Not To Scale

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High Speed Towing Basin Details

- The speed is regulated with an adjustable direct current voltage automatic feedback computerized control system.
- An automatic controller maintains the carriage speed to within ± 0.03 m/s. The maximum carriage speed is 25.7 m/s (50 knots), and the maximum average acceleration rate is 0.49 m/s^2.
- The fresh water in the tank was at a uniform temperature of 20°C, with a kinematic viscosity of 1.01×10^{-6} m^2/s and a density of 998 kg/m^3.
- No measurable change in the water density or viscosity was measured throughout the depth and length of the tank over the duration of the experiments.

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High Speed Towing Basin Details

View Looking East Down the Tank from the Photo Pit

- The High-Speed Basin, which is 904 m long, is comprised of two adjoining sections:
  - (1) a deep-water section at the east end that is 4.9 m deep, 514 m long, and 6.4 m wide
  - (2) a shallow-water section at the west end that is 3 m deep, 356 m long, and 6.4 m wide
- The water level in this test was lowered to allow the tow point to be raised above the surface of the water.

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High Speed Towing Basin Details

Back view of Carriage 5

- The carriage is propelled by 16 weight-bearing vertical drive wheels and 16 horizontal driving guide wheels.

Tow Strut on Carriage 5

- The tow point on the twin tow strut was raised while reversing to the west and lowered between 40.5 and 139.9 centimeters below the surface for test runs.

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Test Setup for Towing the Full-Scale Array

- The test setup was configured for towing a full-scale diameter experimental array of length 129.9 meters from the twin tow strut mounted on Carriage 5.
- An eye bolt attachment served to connect the load cell and the array. This tow point assembly was approximately 20.3 centimeters long from the twin tow strut horizontal plate to the leading edge of the array.
- The array data coax cable ran along the tow point under the fairing and up to the onboard computer.
- The strut was lowered into the tank, to a desired depth and lifted to make adjustments to the load cell at the tow point.
- The tow point was approximately at the centerline of the tow tank; therefore the cylindrical boundary layers on the array had ample room to grow unobstructed.

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Test Setup for Towing the Full-Scale Array

- Due to the length of the array, very small angles of tow can result in significant towing depths at the aft end of the array. For example, if the angle is constant down the array, a tow angle of 5 degrees would produce an array depth of 11.3 meters at the aft end.
- Although the tow tank is the largest facility available, there nevertheless were constraints due to the large geometry of the array tested.
- The vertical and horizontal fairings on the twin tow strut were designed to minimize form drag and minimize vortex shedding. Tare runs with no array were performed to measure the velocity field generated by the twin tow strut.
- The twin tow strut was designed to be sufficiently rigid to minimize vibration, and also aligned to minimize lift.

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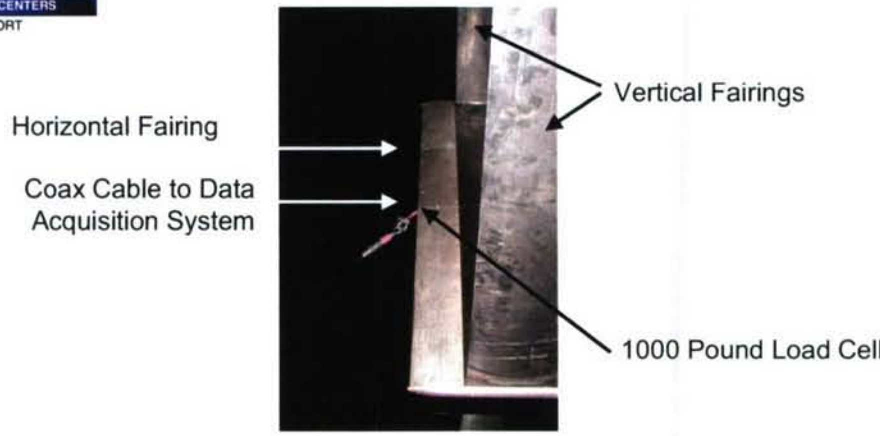
Twin Tow Strut on Carriage 5



- The load cell was mounted at the tow point. The array data passed through a coax cable whose length was sufficient to simulate the impedance of a full-length array tow cable.
- For each time series of load cell data, the mean value was calculated while the carriage speed was at steady state.

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Test Details: Procedure for Handling the Array

- This was the first time a full-scale array was tested without the use of a handling system.
- During test runs, the array was towed behind the carriage from the west end of the basin to the east end. A procedure was developed to prevent the carriage from traversing back over the array which was slightly negatively buoyant. This procedure prevented permanent damage due to bending, kinking, or dragging on the tank bottom. It also provided clearance for the array above the SPIV system while reversing.
- A double-hulled aluminum boat (punt) was used to manage the array before and after the runs. The punt was outfitted with a small electric 1 HP fishing motor.
- The punt traveled east following the carriage after each run commenced. When the carriage stopped, the tow strut was raised, such that the array could be reached from the punt.
- Two buoys were then attached to the array (middle and aft) for flotation.

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Test Details: Handling the Array

- After the second buoy was attached, the end of the array was connected to the punt as shown below. As the carriage returned west at approximately 1.5 knots, the punt traveled at the same speed maintaining at least 10 pounds of tension on the array.
- At the west end the buoys were untied, the array was released, and the tow point placed at the proper depth for the following run.
- During this procedure, communication between the boat and carriage using walkie talkies was required.

Array Aft End Attached to Boat

Array Passing Over SPIV System

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Schematic of Experimental Array

Tow Point	Coax Cable	FIM	O/E	DUMMY	E/O		SM1a	O/E	AIM	ATM

attachment to tow strut

Dry end data acquisition system on carriage

Overall length of Array = 129.8 m

Distance from tow point to wall pressure sensor array is 94.8 m

- FIM: Forward Interface Module
- O/E: Optical to Electrical Module
- Dummy Module: Used to Increase the Array Length
- E/O: Electrical to Optical Module
- SM1a: Sensor Module Housing the Wall Pressure Array
- AIM: Aft Interface Module
- ATM: Aft Termination Module

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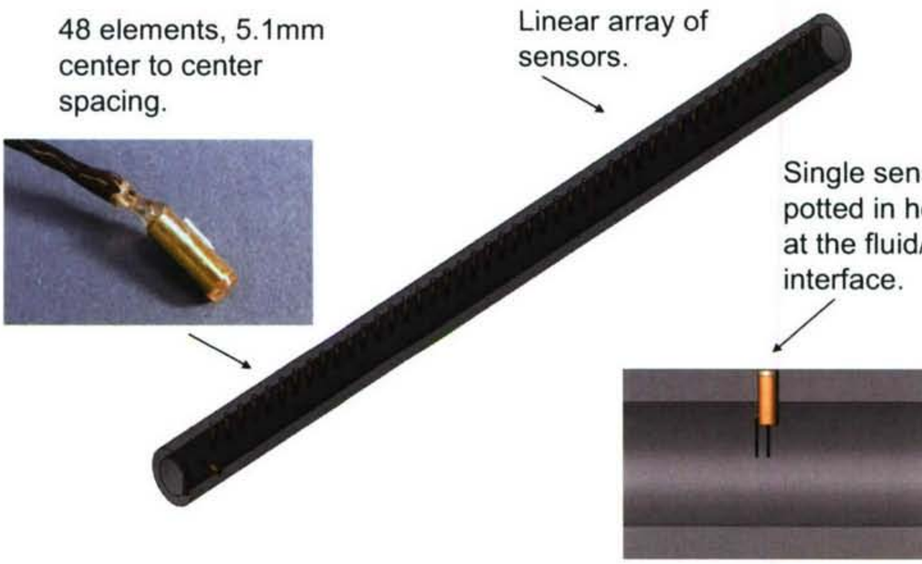
Test Details: Wall Pressure Sensor Array

48 elements, 5.1mm center to center spacing.



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Test Details: Wall Pressure Sensor Array

Wall Pressure Array

Array as Seen from the Photo Pit in the Tow Tank

- The wall pressure sensor array collected time series data throughout the run and the SPIV system simultaneously collected boundary layer velocity data along the entire length of the towed array.
- These two types of data lead to a better definition of towed array stresses and forces due to turbulent boundary layer forcing.

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Testing and Data Acquisition Details

Tow Speed U_o (m/s)	Distance towed (m)	Number of Samples	Number of ensembles averaged
6.22	311.0	100000	97.7
7.77	349.7	90000	87.9
9.33	373.2	80000	78.1
12.96	518.4	80000	78.1
15.55	466.5	60000	58.6
Acceleration from 6.22m/s to 12.96m/s	15.9	12000	11.7

- The array signals were processed using an existing towed array telemetry system, which allowed the signals to be low pass filtered, digitized, and recorded.
- At most tow speeds, the typical run length at steady state was greater than 30 seconds and consisted of 50–100 records (1024 samples each).
- At the higher tow speeds, the typical run length at steady state was 15 seconds and consisted of approximately 40 records.
- The run time was constrained by the length of the array and the usable length of the tow tank.

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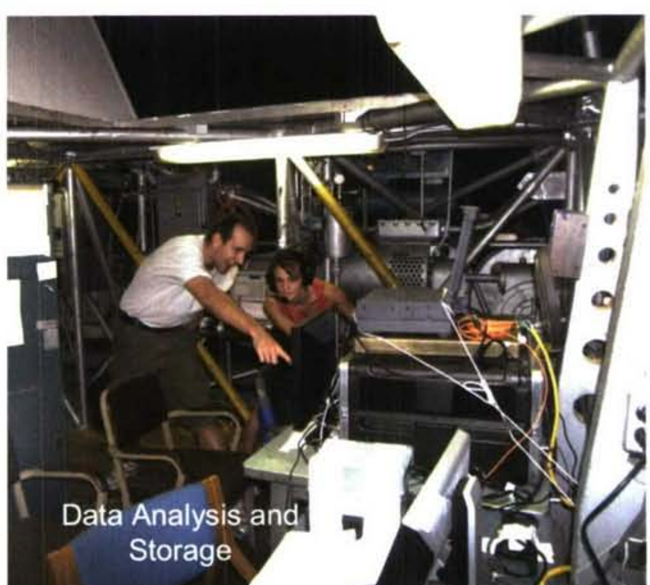
Data Acquisition Equipment on Carriage 5



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Test Details: Test Log

Date	Run Name	Speed (kts)	Tension (lb)	Run Type
June 12th	1-2.	12	165	steady state
June 13th	3	12	165	
	4-5.	15	256	
June 14th	6-9.	15	256	
	10-12.	18	357	
June 15th	13-18.	18	357	
	19	15	256	
	20	25	650	
June 18th	21-24	12--25	varying	acceleration
	25-29	12	165	steady state
June 19th	30-32	12	165	
	33-42	25	650	
	43	30	913	
June 20th	44	12	175	
	45	18	380	
	46	25	700	
	47-48	12	175	
	49	18	180	
	50	25	670	
	51-53	30	920	

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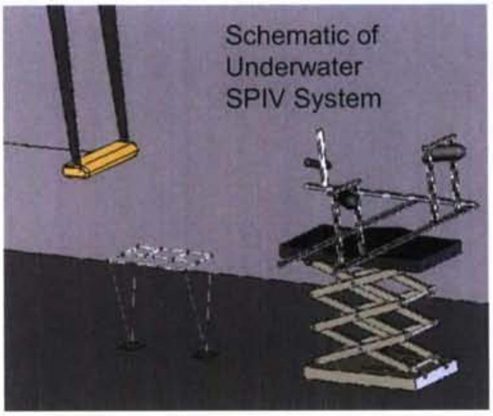
Test Details: SPIV Measurements

- Stereo particle image velocimetry (SPIV) measurements with a transverse laser sheet at a fixed location are used to determine the mean and fluctuating velocity profiles on the array.
- The activated laser head defines the field of view by creating a light sheet across the tank.
- As the array passes through the field of view, the underwater cameras take continuous photographs of micro-spheres (suspended and moving with the flow) which are illuminated by the laser head.
- Computing the displacements of the particles over time produces a 3-dimensional velocity vector field around the array.

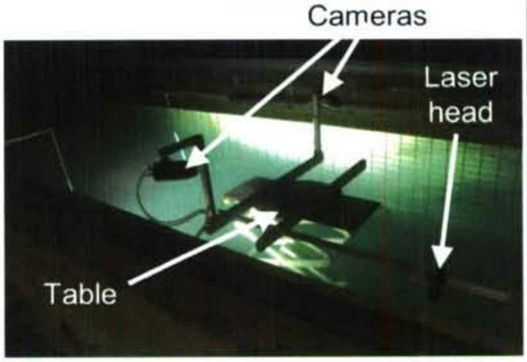
Test Details: Submersible SPIV System

- The SPIV measurements took place at the photo pit located 488 meters from the west end of the tow tank.
- This section of the tow tank is equipped with underwater lights and a submerged table with cameras and a laser head.



Test Details: SPIV System Design

A submerged hydraulic lift adjusted the height of the cameras and laser head to place the field of view at the depth of the array for each speed.



The two cameras on the table were angled at 30 degrees from the line of the tank and directed at the field of view.

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Test Details: Seeding the Field of View

- A 1.2 m x 1.2 m PVC tube frame with regularly spaced holes was tethered to the bottom of the tank with a pulley system. Buoyant foam was attached to the frame for flotation.
- The ropes on the pulley system lifted the frame to the height of the field of view before seeding.
- A sump-pump sent a mixture of micro-spheres and water from the mixing barrel to the PVC frame through a hose connected to the center of the tube frame.
- The micro-spheres spread out into the tank through the holes in the PVC tubes where they were mixed with an extended broom reaching down into the field of view. The goal was to achieve a uniform distribution of particles.

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Test Details: SPIV Data Acquisition

- Two different time intervals between laser flashes were chosen for each speed. The longer time interval showed details of the outer region of the turbulent boundary layer velocity profile whereas a shorter time interval showed details of the velocity profile near the array.
- Two computers were used to collect images from the two cameras.
- The laser was controlled and powered by a third computer. Between each run, the laser is placed in a low power mode.
- The laser started flashing in synch with the cameras collecting images when a reflective strip on the carriage tripped an optical trigger on the side of the tow tank.
- The trigger was timed to start the SPIV collection when the tow point reached the photo pit.

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SPIV Parameters

- SPIV Field of view = 0.9 m x 0.9 m (3 ft x 3 ft).
- Vector resolution = 3.6 mm.
- Camera frame rate = 12 Hz (6 image pairs per second).
- Velocity measurements acquired over entire length of array.
- Approximately 40 image pairs per location.
- Test Speeds: 12-30 kts (6.2 to 15.5 m/s).
- Estimated Reynolds number based on momentum thickness, $Re_{\theta} = 10^6$.
- Maximum arc length Reynolds number, $Re_x = 2.0 \times 10^9$.
- Pressure sensor array located 311 feet downstream of towpoint.

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SPIV Data Analysis

- Average velocity values measured in the strut wake with no cylinder were subtracted from the measured cylinder data to remove any residual mean velocities and turbulence levels caused by the towing strut at each speed and axial location.
- Previous results show that the boundary layer develops slowly along the array, therefore all planes of data occurring within each 10 meter increment of the cylinder length are averaged together. If the data supports a symmetric flow field around the cylinder, then azimuthal averaging will also be applied.
- The resulting velocity profiles will be used to determine the average boundary layer thickness and momentum thickness for each axial location. These parameters are used for scaling the wall pressure spectra and velocity data.
- Fluctuating velocities will be calculated for each ensemble plane of data and used to evaluate average turbulent velocity profiles.

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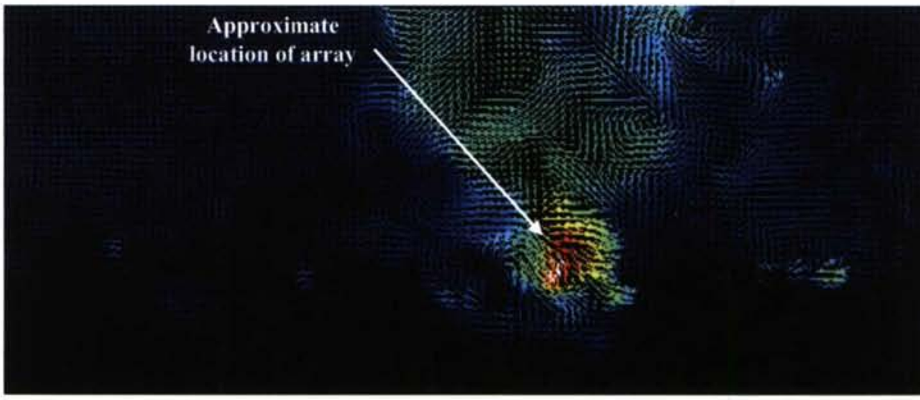
Experimental Results: Sample 3 Dimensional Velocity Field



- Plane orthogonal to the cross section of the array.
- Color map denotes the magnitude of the velocity vectors out of the plane and the length of the vectors represents the magnitude in the plane.
- Highest velocities (red) occur near the array surface, and the field does not appear to be symmetric in this example.

Wavenumber Frequency Spectra Analysis

- The wavenumber frequency spectra are computed from discrete time records acquired simultaneously from all of the wall pressure sensors in the array, and provide a statistical description of the space-time pressure field.
- The spectra are used to determine different sources of flow noise, which include convective energy, structural energy in the array, and background acoustic noise. Each of these sources has distinct characteristics such as wave speed and exist over specific ranges of wavenumber and frequency.
- At frequencies where the background acoustic noise is high, the wavenumber frequency spectra allow other contributions to be isolated and identified. Useful flow noise measurements can therefore be made in facilities not designed to be acoustically quiet.

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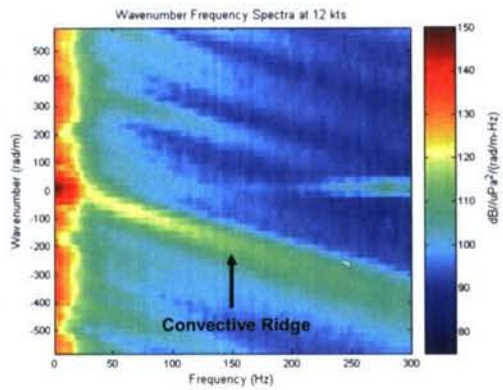
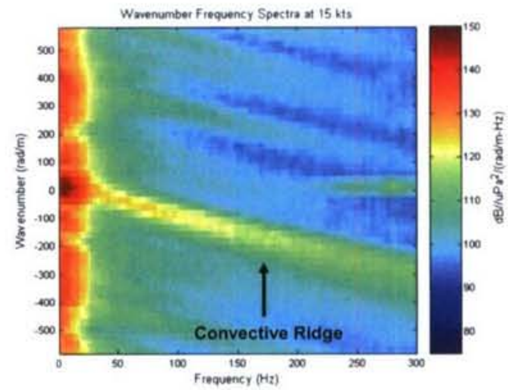
Test Results: Wall Pressure Wavenumber Frequency Spectra



Towing Speed 6.2 m/s



Towing Speed 7.8 m/s

Measured Wavenumber Frequency Spectra with the 48 element array. A well defined convective ridge exists, whose slope can be used to determine the convection velocity of the turbulent structures. The array towed in a stable configuration at tow angles less than 1 degree.

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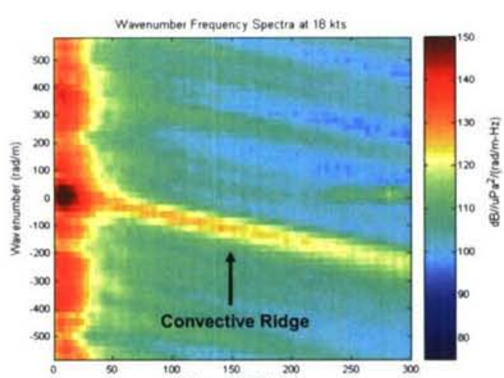
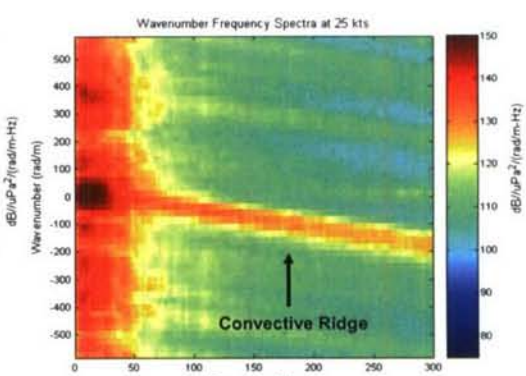
Test Results: Wall Pressure Wavenumber Frequency Spectra



Towing Speed 9.3 m/s



Towing Speed 13.0 m/s

The slope of the convective ridge increases with increasing tow speed, and the energy levels also increase.

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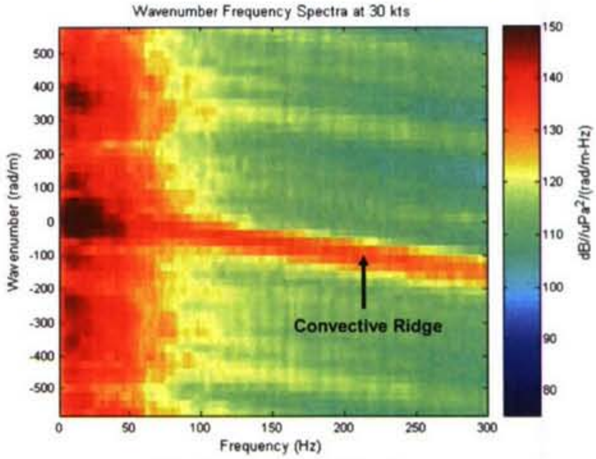
Test Results: Wall Pressure Wavenumber Frequency Spectra



Towing Speed 15.6 m/s

High energy levels at low frequencies reflect flow induced vibration of the array. These levels are broad in wavenumber.

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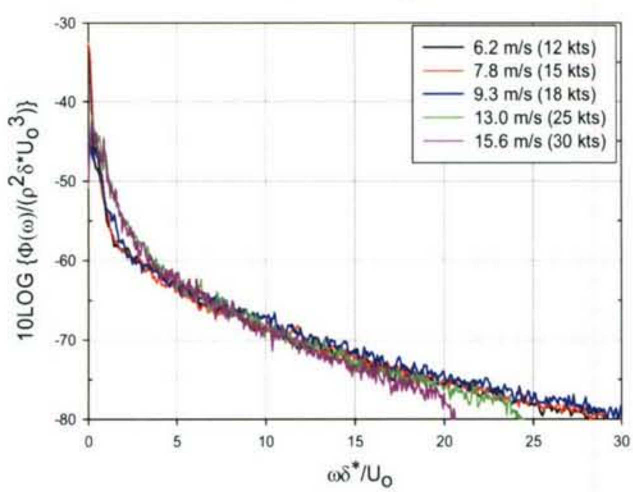
Test Results: Scaled Wall Pressure Autospectra

Outer Scaling



Autospectra of the wall pressure fluctuations nondimensionalized with outer turbulent boundary layer variable scaling, which provides a good collapse of the data.

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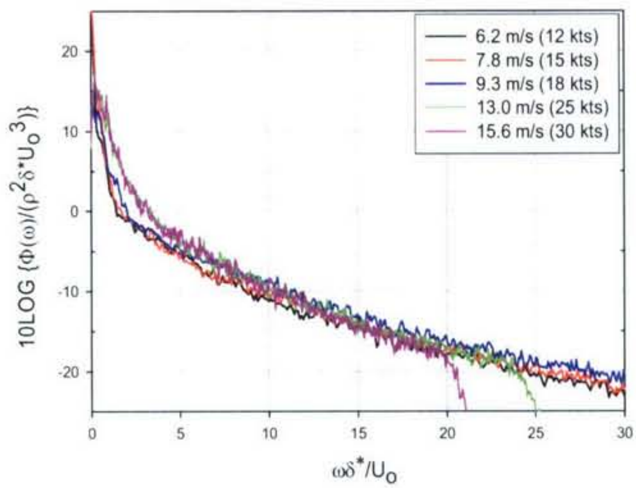
Test Results: Scaled Wall Pressure Autospectra

Mixed Scaling



Autospectra of the wall pressure fluctuations nondimensionalized with mixed turbulent boundary layer variable scaling, which also provides a good collapse of the data.

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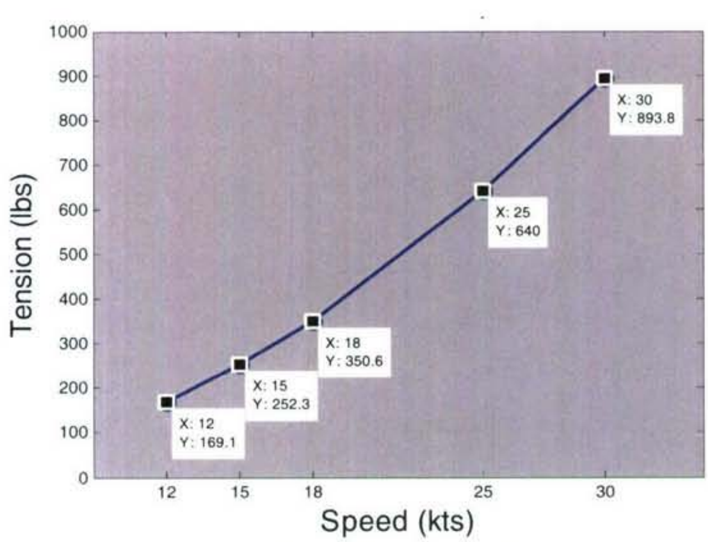
Test Results: Array Mean Tension



Measured values for tension were higher than for a comparable flat plate due to the cylindrical turbulent boundary layer.

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Summary

- These tests represented the first full-scale towed array experiments at the Model Basin using Carriage 5.
- The results demonstrated the ability to measure turbulent boundary layer fluctuations using a linear array of sensors.
- The advantage of this facility over sea or lake trials is the ability to make SPIV measurements of the velocity field.
- Experimental testing of the array in the Model Basin is necessary because of the scale of the model tested, the required tow speeds, and related Reynolds numbers.
- The tests were very successful with data analysis ongoing.
- Additional testing is planned for FY-08.

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DISTRIBUTION LIST

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